OBSERVABILITY OF INDIGENOUS ORGANIC MATTER ON THE MOON

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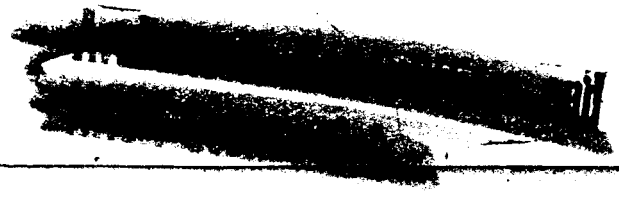

SUMMARY

The theories of Gilvarry and Sagan implying the presence of indigenous organic matter on the Moon are reviewed briefly, for comparison. The former postulates the presence in the lunar maria of organic remains derived from a pristine biota in a hydrosphere formed by exudation from the Moon's interior and lasting several billion years. The latter assumes the presence of organic matter on the lunar highlands, now covered by meteoritic infall, formed by the action of solar ultraviolet light and other agencies on a reducing protoatmosphere lasting significantly less than a billion years. However, the fact that meteoritic infall on a moon without an atmosphere causes a net loss of mass from that body is determinative for observability in the Surveyor and Apollo missions of the organic vestiges postulated in the two theories. On Gilvarry's model, a loss of mass from the lunar surface of at least 7 m in depth is found for the effects of meteoritic impact and sputtering action (by the particles of the solar wind and flares) over the period of several billion years since the atmosphere and hydrosphere vanished. As the organic remains producing the dark color of the maria are assumed distributed throughout the bulk of the sediments in the maria floors, the coloration cannot be destroyed by superficial loss of mass by meteoritic impact. It follows that future lunar explorers should find organic fossils below the depth of roughly 3 to 5 m fixed by the charring action of the most penetrating

radiation, the cosmic rays. Self-consistently on Sagan's theory, no over-all gain of mass by meteoritic action on the Moon could occur, which is at variance with his conclusion of a depth of burial of organic vestiges amounting to some tens of meters. The actual loss of mass on the model after the lunar atmosphere vanished would be at least 10 m in depth, and hence the organic remains postulated as superficially distributed at a remote time would be completely unobservable at present.

INTRODUCTION

In the classical view of the nature of the lunar surface, the dark material in the floors of the maria is identified as lava, primarily because of its appearance in the telescope as dark rock covering regions comparable in area to terrestrial lava flows. However, the lunar surface presents few physical features which can be interpreted indubitably as volcanic, and the presence of lava in the absence of obvious volcanism is very difficult to understand. In recent years, this assumption of the presence of lava has been challenged by Gold (1955) and by Gilvarry (1957, 1958).

In particular, Gilvarry (1960a,b, 1961a, 1962) has presented a self-consistent theory in which the dark coloration of the surfaces of the maria is ascribed to effects of an indigenous biota in a hydrosphere on the Moon at a pristine epoch. Further, Sagan (1960, 1961) has discussed the possibility of deposition on the lunar

surface of organic compounds formed in a reducing protoatmosphere of the Moon. The purpose of this paper is to determine the extent to which traces of such indigenous organic matter might be observed at the present time, on the basis of the two theories in question. The problem is one of obvious importance, in view of the imminence of the unmanned lunar landings of the Surveyor series and the manned mission of Apollo to the Moon planned for this decade.

For prefactory purposes, the two theories in question will be reviewed briefly.

THEORY OF GILVARRY

During the past few decades it has become increasingly clear that the terrestrial atmosphere and hydrosphere were formed by exudation from the Earth's interior. The astronomical evidence consists in the very low abundances of the inert noble gases in the Earth's atmosphere, relative to the stellar abundances. From this fact, Brown (1952) and Suess (1949) have inferred that any element which existed primarily as a fluid (or component thereof) at the time of the Earth's formation could not have been retained to a significant extent. It follows that the present atmosphere and hydrosphere of the Earth are not residual from primodial antecedents, but are of secondary origin, formed by exudation from the interior. The conclusion is supported by geological evidence also (Rubey, 1955).

In view of the Moon's smaller mass, it is meaningless to speak of the lifetime of any atmosphere on the Moon other than the secondary

one formed by a degassing process exactly analogous to that postulated for the Earth. On the hypothesis that the total masses of a constituent in the secondary atmosphere and hydrosphere for the Moon and Earth should be proportional to the corresponding masses of these bodies, Gilvarry (1960a,b) has computed lifetimes of gases on the Moon for thermal escape. Lifetimes are shown in Fig. 1 for H_2O, CO_2, O_2, and N_2, as functions of the assumed temperature at the critical layer high in the lunar atmosphere from which escape occurred. One sees that the lifetime of water vapor is the longest by a large margin for any temperature above 1000°K. Moreover, this lifetime is measured in billions of years, and thus is comparable with the age (of order 4.5×10^9 yr) of the Moon. The old computations of Baldwin (1949) yielded values insignificant on an astronomical scale primarily because he ignored the possible existence of a lunar hydrosphere capable of continuously replenishing the atmosphere. As a further reason, his computations did not include the large effect of the parameter B of Spitzer (1952) or A_j of Gilvarry (1961b,c).

On this theory, sufficient water existed at one time on the Moon to drown all the lowlands and to encroach significantly on the highlands. Accordingly, there should be a systematic difference in the relative dimensions of lunar craters formed by impact of meteorites in water and on land, since experiments carried out by the Atomic Energy Commission in the Pacific indicate that the effect of a water cover is to make the crater considerably shallower than one caused by an explosion on land, other things being equal (Glasstone, 1957).

The correlation of crater dimensions (diameter D vs. depth d) on the basis of the theory of Gilvarry (1960b) is shown in Fig. 2. The average of the curves for craters in hard and soft rock on land is essentially equivalent to Baldwin's curve for lunar craters of his Class I (the least eroded), and includes the points for terrestrial meteoritic craters and craters from nuclear explosions on land. The correlation curve for the circular lunar maria and craters of Class V of Gilvarry is based on the dimensions of a crater, Glasstone (H), corresponding to a nuclear explosion in water over a bottom of hard rock (Glasstone, 1957). Thus, this correlation of dimensions includes the circular lunar maria, of which Mare Imbrium is the archetype, and implies that these features are impact craters now representing the relics of ancient seas. One observes that the craters of Classes IV, III, and II of Baldwin follow intermediate loci in Fig. 2, corresponding, according to this theory, to the variation in water depth as a result of thermal dissipation of the hydrosphere.

Conceivably, these correlations could be caused by a mechanism other than the effect of water. However, one can point to some observational evidence for the pristine presence of a lunar hydrosphere (Gilvarry, 1964a). Further, the theory presented is consistent with the photographs of the surface of Mare Nubium transmitted to the Earth by Ranger VII. Thus, no deep dust exists on a mare, apparently (Hess, 1964; Shoemaker, 1964). In addition, neither the furrows, cracks, and fissures appear (at a resolution less than 1 m) which

one expects in lava sheets (Kuiper, 1964), nor the flow patterns one anticipates in this case (Hess, 1964), as is evident from the photographs published by the National Aeronautics and Space Administration (Anonymous, 1964). The photographs taken by Ranger VIII throw no significantly new light on this question, since they show that Mare Tranquillitatis is essentially similar to Mare Nubium in surface features (Pickering, 1965).

If the analogs of terrestrial oceans were once present on the Moon, it is reasonable to inquire about the presence of a former lunar life. It is in such bodies of water on the Earth that Oparin (1938) postulates the origin of the first living organism. Specifically, he proposes that the primeval atmosphere was reducing in character. This condition would favor synthesis of complex organic compounds, which accordingly would be present in large quantities in the oceans of the primitive Earth. The sources of free energy suggested as the primary agents in biopoesis are ultraviolet radiation from the Sun, and lightning and coronal discharges in the atmosphere (Miller and Urey, 1959). The possibility that infall of large meteorites may have contributed significantly to the requisite free energy has been raised by Gilvarry and Hochstim (1963). In Oparin's viewpoint, the first organisms to appear were necessarily heterotrophic and developed only later into autotrophic ones.

One expects the secondary atmosphere of the Moon to have been reducing in character, similar to that of the pristine Earth. If Oparin's views are correct, and if the maria are indeed ghosts of

former seas, one can argue that the dark color of the sediments now covering the mare floors is derived from a pristine indigenous biota on the Moon, as postulated by Gilvarry (1960b). Note that only a small amount (less than 5%) of organic carbon in a sediment is sufficent to yield a dark rock of low reflectivity (Pettijohn, 1949).

Accordingly, it will be postulated that a pristine form of life once existed in the lunar hydrosphere. Certainly, the time scale shown in Fig. 1 for loss of water vapor from the Moon, as compared to the ages (about 2.6×10^9 yr) of the oldest known Precambrian fossils, is favorable to this hypothesis of a pristine lunar life (Gilvarry, 1960b). Based on Oparin's hypothesis and the time scales involved, a detailed argument leading to the conclusion that a primordial life of simple form in the pristine hydrosphere of the Moon is indeed possible has been presented by Gilvarry (1964b, 1965).

When the lunar hydrosphere and atmosphere finally dissipated, the organic remains in the surfaces of the maria necessarily were exposed to the full effect of solar and cosmic radiation, without atmospheric shielding. Over the course of time, penetration of this radiation to shallow depths would char the organic material to elemental carbon. Disruption, spreading, and mixing of the surface material by the innumerable impacts of small meteorites over the ages must have left a thin layer of dust mixed with carbon over the surfaces of the maria.

For explorers on the Moon to find fossils of the inferred life in which the organic remains are not grossly damaged by radiation, they must go to a depth providing sufficient shielding. This

depth has been estimated by Gilvarry (1964b, 1965) as 3 to 5 m on the assumption that the point at which charring ceases to be significant is fixed by the most penetrating radiation, the cosmic rays. Sagan (1960, 1961) calculates that the temperature at about 10 meters below the surface never rises more than a few degrees above $0^{\circ}C$. If temperatures at this range of depths never fluctuated more than mildly above this upper limit since the organic fossils were laid down, they may be chemically intact at the present time, at least to some extent. This conclusion follows because the half-lives with respect to thermal stability approach the order of the age of the Earth for many organic molecules, provided the temperature is restricted to the low values in question (Abelson, 1954).

THEORY OF SAGAN

Sagan (1960, 1961) considers the possibility of a secondary lunar atmosphere formed by a degassing process from the interior of the Moon, on the basis of analogy with the Earth. He estimates that such an atmosphere will escape to space in roughly 10^3 years, if there is no replenishment from the interior. Otherwise, with replenishment, he estimates a possible lifetime of the primordial lunar atmosphere as perhaps 10^7 to 10^8 years. The basic difference in Gilvarry's theory lies in the hypothesis that not only an atmosphere but also a hydrosphere was exuded from the Moon's interior primordially, in <u>complete</u> correspondence with the case for the Earth.

The atmosphere postulated by Sagan is reducing, and hence the effect of solar ultraviolet light (and electric discharges) would

be to produce molecules of fair complexity (up to a molecular weight of roughly 100 on Sagan's estimate) which reached the lunar surface by gravitational diffusion. For such organic material to survive the effects of continued radiation and high temperature on the Moon after dissipation of its atmosphere, Sagan invokes the presence of a protective covering formed by meteoritic infall. Using the figure of Whipple (1958) for the rate of meteoritic fall, he estimates a depth of burial of some tens of meters. Such a depth of burial (if true) would be more than sufficient to protect the organic products from the effects of cosmic rays and solar radiation and from the extremes of temperature on the surface of a Moon without an atmosphere. Further, many of the molecular constituents would have survived to the present day, in view of the half-lives for thermal stability at the low temperatures one expects at such a level of burial (Abelson, 1954). Thus, on Sagan's theory, future lunar explorers should be able to find organic matter localized at depths of some tens of meters below the lunar surface. Sagan asserts that these chemical vestiges should exist only in the highlands, in view of the presumed presence of lava flows in a mare.

Note that the theories of Gilvarry and Sagan are not mutually exclusive, as regards essential concepts. In fact, the process of formation of organic molecules contemplated by Sagan is an essential preliminary step in the sequence of events leading to evolution of a biota envisaged by Gilvarry. What is at issue is the degree to which the process continued, in view of the different estimates of the time scales for retention of an atmosphere and hydrosphere.

EFFECTS OF METEORITIC INFALL

In the preceding discussion, mention has been made of Sagan's estimate of the depth of burial of organic products, arising from the effect of meteoritic infall in blanketing the surface of the Moon. A further consideration is the possible loss of superficial material from the Moon, as a consequence of meteoritic impact.

This question has been discussed theoretically by Gilvarry (1964c). Subsequent to loss of the Moon's atmosphere, a falling meteorite suffers no atmospheric deceleration, and the minimum velocity at the surface is the Moon's escape velocity - 2.4 km/sec. The one-dimensional model of the impact of a large meteorite treated by Gilvarry and Hill (1956a,b) is sufficiently reliable to justify the statement that in the explosion resulting from collision of a meteorite with velocity V on the lunar surface, the order of the resulting flow velocities directed away from and tangent to the surface ranges up to V, even in the three-dimensional case. Thus, impact of a meteorite on the Moon with the lowest possible velocity, the escape value, yields fragments traveling with velocities of the same magnitude into space, and these fragments are derived both from the body of the meteorite and from the lunar surface. At the higher velocities, the usual scaling laws imply that the mass of the meteorite becomes asymptotically small relative to that corresponding to the crater interior (Hill and Gilvarry, 1956). In this limit, at least, one expects that the net effect of meteoritic infall on the Moon is to produce an over-all <u>loss</u> of mass from this body.

This deduction is in agreement with results of Anders (1962) for a projectile velocity as high as 30 km/sec. He estimates from the numerical analysis by Bjork (1961) of the impact at Meteor Crater in Arizona that a mass exceeding the projectile mass by a factor of about 14 was ejected at a velocity exceeding the lunar escape velocity in this event. By the same means, Bjork (1962) has obtained a more accurate figure of about 10.

Note that the argument given does not hold in the presence of an atmosphere, as in the case of the Earth. The presence of the air causes melting, ablation, and volatilization of entering meteoroids, which transfer mass to the atmosphere and eventually to the Earth. As a consequence, only large meteorites moving at high velocity can reach the Earth's surface (Gilvarry and Hill, 1956b). Subsequent to impact at the surface, atmospheric deceleration prevents the large majority of the fragments from maintaining escape velocity.

Sputtering of the lunar surface in the absence of an atmosphere by the particles of high energy in the solar wind and flares should cause a further loss of mass beyond that due to meteoritic impact (Gilvarry, 1964c). Note that the ejection velocity of a sputtered atom is typically of the same order of magnitude as that of the incident atom (some hundreds of kilometers per second for an energy in the range of 1 kev), so that a sputtered atom cannot be captured by the Moon's gravitational field, in general. The effect of an atmosphere obviously depends on its density. However, an atmosphere as dense as that of the Earth has sufficient stopping power to prevent loss of mass from the actual surface of the planet.

OBSERVABILITY OF ORGANIC REMAINS

The absence or presence of an atmosphere on the capturing body clearly is crucial in determining whether loss or gain of mass results from meteoritic influx. In this section, the question will be discussed quantitatively for the Moon, as it affects the observability of organic remains on Gilvarry's and Sagan's models.

To determine the loss of mass from the surface of the Moon after it lost its atmosphere, the figure of Whipple (1958) for the rate of meteoritic infall is available. It is necessary to assume, with Sagan, that this meteoritic flux has been constant throughout the aeons. However, two values have been quoted above for the ratio of the loss of lunar mass to the meteoritic mass, applying to a special case. To obtain a lower limit to the loss of mass, the ratio in question will be assigned the value unity. Note that a range of 2 to 3 billion years has been estimated for the lifetime of the lunar hydrosphere on the theory of Gilvarry. Corresponding to the smaller of the two numbers, a figure of 2.5×10^9 yr B. P. will be accepted as the time when the lunar hydrosphere and atmosphere vanished completely, on the model.

For this period of time before the present, details of the calculation to obtain the depth of superficial material lost from the Moon by meteoritic impact are presented in the first line of Table I. The loss of surface density through this mechanism is converted to a depth of loss by taking the material density on the Moon's surface as 3, which is about the mean density of the satellite. Thus, this choice of

density implies that the thickness of the layer of dust on the Moon's surface is relatively thin (less than the mean diameter of the impinging meteorites), consistently with results inferred from the photographs (Hess, 1964; Shoemaker, 1964) taken by Ranger VII. The loss (indicated by the negative sign) of mass corresponds to a depth of 5 m over the surface. The actual figure probably is considerably larger, in view of the ignorance of the true ratio of the loss of mass to that of the impinging meteorite and the dependence on the unknown porosity of the superficial layer of the Moon.

Gilvarry (1964c) has estimated the mean flux density of sputtered atoms from the Moon; the value is given by the second entry in the fourth column of Table I. It will be assumed that the dominant part of the sputtering loss occurred from the surface of the superficial dust layer on the Moon and not from the solid rock beneath; the corresponding material density shown in the penultimate column is from data of Wesselink and Smoluchowski for dust in vacuo (Gilvarry, 1958). The loss is small relative to that produced by meteoritic action.

The lower limit (5-7 m) on the depth of loss of superficial material calculated for the Moon after dissipation of its atmosphere is of the same order as the estimated depth (3-5 m) at which fossils undamaged by radiation might be found. However, the theory of Gilvarry presupposes the presence of organic material derived for a biota throughout the sediments. Further, Sagan calculates that in the space of a few months to years, essentially all molecular bonds would be

broken and complete charring would occur in any organic compounds exposed to the full intensity of the solar wind and flares on the lunar surface. Hence, any organic remains initially at depth in the sediments and brought to the surface by a meteoritic impact on a mare would rapidly be charred to carbon. Thus, the new surface constantly created in this manner was continuously denigrated by the solar wind and flares. At depth, decomposition proceeded continuously to a depth of some meters on a much shorter time scale, by virtue of the penetrating cosmic rays. Thus, the estimated figure for the depth at which undamaged fossils might be found should be relatively insensitive to the effect of loss of mass by meteoritic impact. It follows that the superficial dark color of the maria has a regenerative capacity, in that it cannot be destroyed by meteoritic impacts.

It is a matter of interest to determine the actual depth corresponding to gain or loss of superficial material from the Moon self-consistently on Sagan's model, on the basis of Whipple's value for the rate of meteoritic infall. The maximum lifetime for a lunar atmosphere implied by Sagan's discussion is 10^8 yr; only for this period of time during the Moon's infancy was accretion possible. Details of the calculation appear in the penultimate line of Table I. The material density of the meteoritic matter accreted by the Moon is taken as 0.4 gm/cm^3, corresponding to the estimate of Whipple (1963) for the density of meteoritic material of cometary origin. The depth of burial of the organic material according to the theory of Sagan

actually is only about 2 m as an upper limit, as contrasted to his estimate of some tens of meters. The difference arises because Sagan tacitly assumed that the Moon could accrete meteoritic material throughout its lifetime, or for a period of at least 10^9 yr (during which no atmosphere existed, on his model).

However, when accretion stopped after dissipation of the Moon's atmosphere, the surface of the Moon became subject to loss of mass by virtue of meteoritic impact and sputtering action. On Sagan's model, these processes actually occurred for a time of the order of the Moon's age, or about 4.5×10^9 yr. From the numbers in the last row of Table I, one sees that the depth corresponding to this loss is at least 10 m, exceeding the actual depth (rather than Sagan's estimate) of prior burial by an order of magnitude. Further, the depth probably is considerably greater, since the data of Table I are based on the assumption that the ratio of the loss of lunar mass to that of an impinging meteoroid is unity. If this ratio is as high as Bjork's estimate of 10, the depth corresponding to loss of mass after escape of the atmosphere exceeds that for gain during the prior retention by at least two orders of magnitude, on Sagan's model.

It follows from these considerations that the layer of organic material postulated by Sagan as existing on the lunar surface at a pristine epoch is <u>completely unobservable at the present time</u>. At the present epoch, this organic material would have been dissipated into space by the action of meteoritic impact and particulate radiation over the aeons.

DISCUSSION AND CONCLUSIONS

Gilvarry's figure of 3 to 5 m for shielding of organic remains in the superficial crust of the maria was estimated with disregard of loss of surface material on the Moon through the agencies of meteoritic impact and solar radiation. The closer discussion given here, however, shows that even when these factors are considered the approximate figures for the depth should be essentially correct. Thus, it should be possible on the basis of Gilvarry's theory for unmanned spacecraft of the Surveyor series or manned vehicles of the Apollo mission to find direct evidence of a pristine lunar life by observations on the surface of a lunar mare, in view of the stability of chemical compounds at the subsurface temperatures one expects at depth. If organic matter is found on the Moon in the planned period of exploration over this decade, it would represent a strong indication that Gilvarry's theory is correct.

It has been established that the layer of organic material postulated by Sagan as existing on the lunar surface at a pristine time is unobservable at the present epoch. This is not to say that the theory is false. The only implication of the results in this connection is that direct evidence as to the truth of Sagan's hypothesis can no longer be obtained. Thus, if evidence for organic material on the Moon is found by the Surveyor and Apollo missions, one cannot look to Sagan's theory for its origin.

Not only do these considerations rule out the possibility of observing vestiges of organic compounds on the special theory of

Sagan, but a stronger result can be stated. Any mechanism which deposited organic compounds or biological remains only superficially on the surface of the Moon at a distant epoch in the past will yield vestiges unobservable at the present time. The result follows because of the unavoidable dissipation of the traces into space by the action of meteoritic impact and particulate radiation over the time since the Moon lost its atmosphere and hydrosphere.

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TABLE I

Contributions of Meteoritic Infall and Sputtering Loss to the Superficial Layer of the Moon

Theory	Mechanism	Time yr	Flux density gm/cm^2 sec	Gain or loss of surface density[a] gm/cm^2	Material density gm/cm^3	Depth of gain or loss[a] m	Type of Limit
Gilvarry	Meteoritic loss	2.5×10^9	2×10^{-14}[b]	-1500	3	-5	Lower
Gilvarry	Sputtering loss	2.5×10^9	-4×10^{-15}[c]	-300	2	-2	Mean
Sagan[d]	Meteoritic gain	1×10^8	2×10^{-14}[b]	+60	0.4	+2	Upper
Sagan[d]	Meteoritic loss	4.5×10^9	2×10^{-14}[b]	-3000	3	-10	Lower

[a]The negative sign implies a loss.

[b]Figure of Whipple (1958) corresponding to incoming meteoritic flux.

[c]Figure of Gilvarry (1964c) for sputtering loss.

[d]Theory of Sagan as corrected for proper periods of meteoritic gain and loss of mass in this work.

FIGURE LEGENDS

Fig. 1. Lifetimes of various constituents of the primitive lunar hydrosphere and atmosphere, as a function of assumed temperature in the escape layer at the top of the atmosphere. The curves for O_2 and N_2 are indistinguishable on the scale used.

Fig. 2. Correlation of diameter D as a function of depth d for various classes of craters and the circular lunar maria. The solid curves correspond to fitted functions for craters on land and in water, applying to lunar craters of Classes I (including IH and IS) and V (including the lunar maria), respectively. The craters of Classes IH and IS are those of Class I lying in the highlands (hard rock) and the maria (soft rock), respectively. The correlation curves for lunar craters of Classes II, III, and IV are shown dashed. In general, points for only every tenth lunar crater in Classes IH and IS appear.

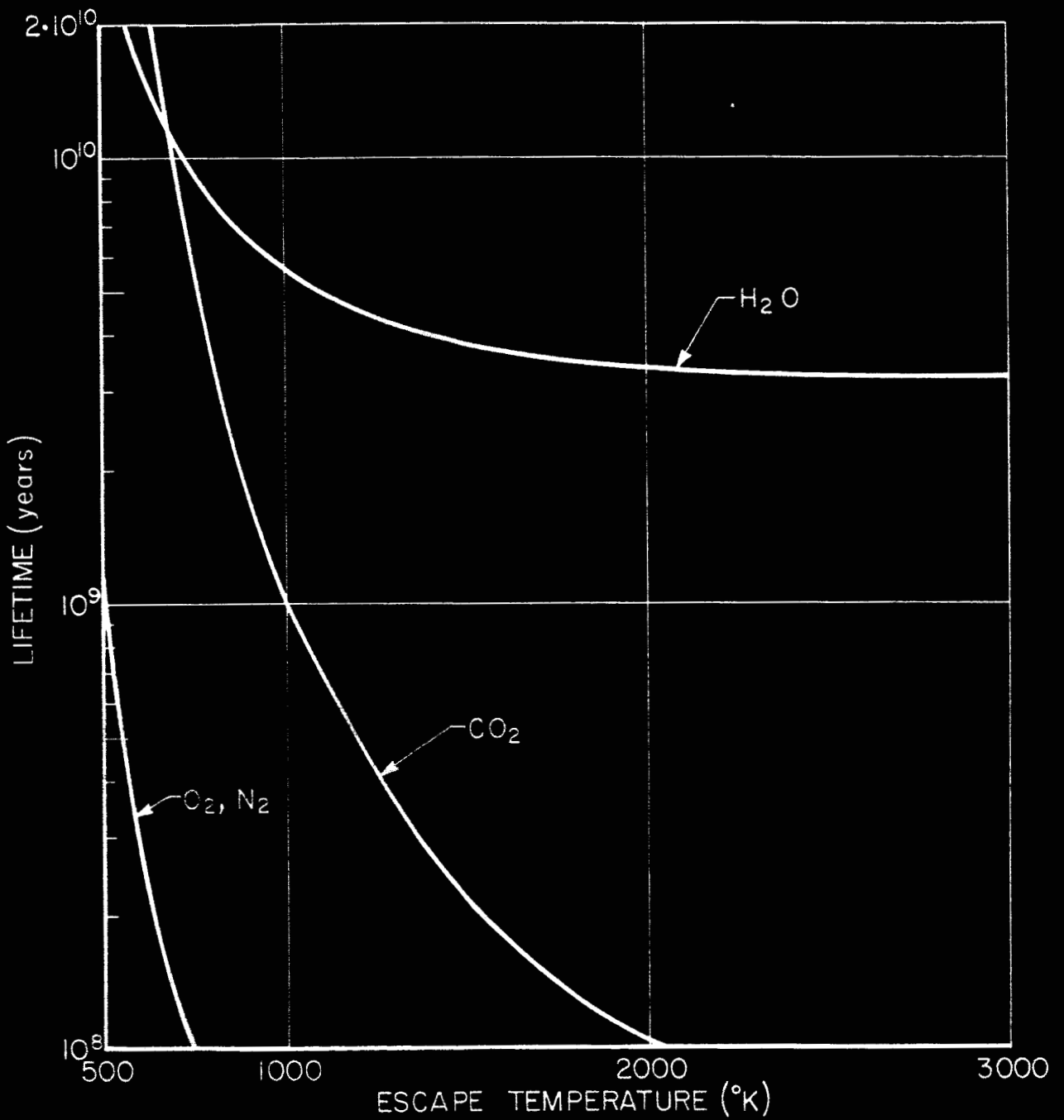

Figure 1

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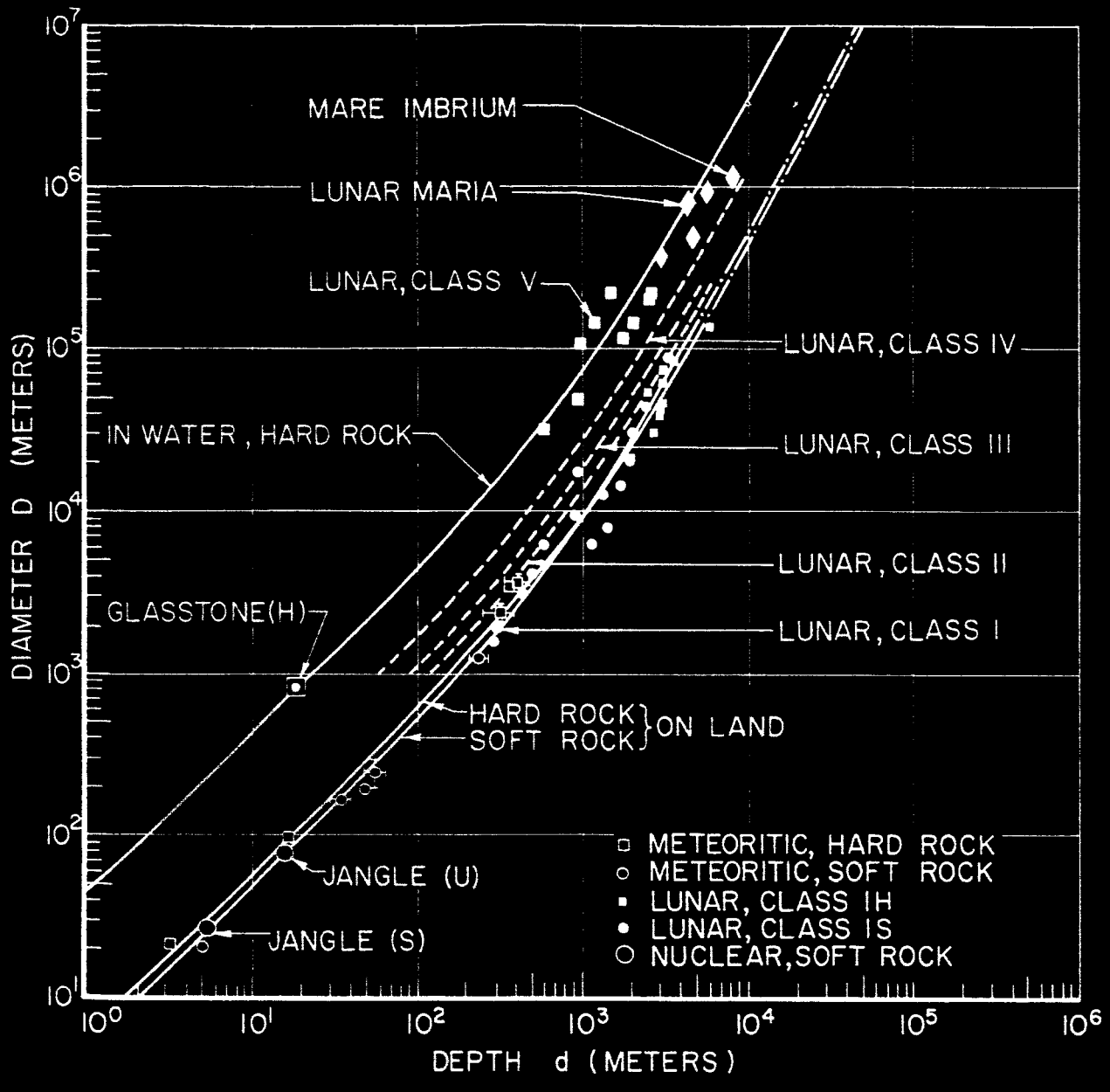

Figure 2

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